RC BEAMS AND SLABS EXTERNALLY REINFORCED WITH FIBER REINFORCED PLASTIC (FRP) PANELS

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ABSTRACT

Considerable experimental and analytical studies concerning the external reinforcement of RC beams and slabs using fiber reinforced plastic (FRP) strips and panels have been accomplished in the past ten to twelve years. This paper will review the pertinent work in this area and in particular will review and present both experimental and analytical studies conducted by the United States Air Force at Wright Laboratory's Pavements and Facilities Section (WL/FIVCO), Tyndall Air Force Base, Florida.

Both experimental and analytical studies at WL/FIVCO have shown that RC beams and slabs retrofitted with carbon fiber reinforced plastic (CFRP) and Aramid fiber reinforced plastic (AFRP) show considerable flexural strength increases when compared to control beams without the FRP panels. These studies have been conducted on structural response to static loads, drop weight dynamic loads and blast loadings from conventional explosives. In all cases considerable strength enhancement has been observed. For beams retrofitted with bottom tensile CFRP strips the largest strength enhancement occurred for RC beams with steel reinforcing ratios of 1.5 percent or less. This corresponds to a ratio of steel area (tension only) to CFRP area of approximately 4.0 or less.

In cooperation with WL/FIVCO, the University of Florida developed a vacuum bond technique to apply prefabricated FRP panels to concrete surfaces using a commercial high performance epoxy adhesive. In addition to beam and slab structural response, WL/FIVCO has conducted tests of freeze-thaw cycling, ultraviolet exposure, heating, cooling, wetting and drying on concrete samples with and without various FRP strips. No detrimental effects were observed for these tests. Fatigue strength of externally reinforced beams (no steel) was also studied at WL/FIVCO using a non-reversed fatigue loading of 80 and 10 percent of static maximum load applied at a rate of 20 Hz for 2,000,000 cycles.

Based on results obtained in the WL/FIVCO studies, one span of a four girder multispan RC highway bridge was retrofitted by Auburn University with side glass fiber reinforced plastic (GFRP) and bottom CFRP. Traffic tests before and after retrofit of the bridge span showed an approximate 12 percent reduction of both midspan displacement and rebar strain of those of the unrehabilitated bridge span.

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INTRODUCTION

The use of aerospace fiber reinforced plastic panels to strengthen and rehabilitate concrete slabs, beams, and columns has been described in several articles in technical reports, journals and trade magazines. A technical report by the author[1] and a dissertation by Jerome[2] lists many of these papers and they shall not be listed here. Recently, a series of analytical and experimental studies on various fiber reinforced plastic (FRP) strips and panels used to externally reinforce concrete beams and slabs, have been conducted by Wright Laboratory's Pavement and Facilities Section (WL/FIVCO), Tyndall AFB FL. The overall objective in these studies is to understand the structural response and interaction of the concrete and FRP under various loading conditions. At the onset of this study very little data and only seven to eight references were available on this subject. In order to obtain fundamental knowledge of the interaction of these materials, the study began with very basic and uncomplicated experiments. These studies began with small unreinforced laboratory specimens tested statically in a standard material test machine and dynamically in a drop weight tester. Tests and analyses have continued with full scale beams tested statically in a three point flexural device as shown in Figure 1. These studies were continued with dynamic field tests of full scale slabs in Israel. Further studies are planned for full scale dynamic beam and slab tests at Tyndall AFB and field tests in Israel. Experimental tests and analyses of beams and plate response, durability and a rehabilitation project for external fiber reinforced/concrete structures and materials are discussed in the next sections.

BEAM EXPERIMENTS AND ANALYSES

Small laboratory plain concrete beams with CFRP laminate cemented to the bottom and sides of these beams were tested at Wright Laboratory' Pavements & Facilities Section in the spring of 1992, and showed considerable strength enhancement over beams without CFRP. These tests are reported on by Strickland and Hughes.[3] These tests results showed bending load capacities could be increased rather significantly by bonding CFRP panels on the tensile side of the beam. Low load shear and diagonal tension failures could be reduced by duplication of CFRP panels on the beam sides. The testing of internally unreinforced small laboratory specimen does very little in the understanding of RC beams with external FRP but does have the advantage of low cost. Also, the small specimen with external FRP does allow for the study of the effect of the FRP on strain distribution through the beam depth. For conventional steel reinforced concrete beams, a shift in the neutral axis occurs as the tensile portion of the bending stress exceeds the tensile strength and cracking occurs. This tensile cracking and subsequent shift in the neutral axis was observed experimentally in the strain distribution measured on the bottom, sides, and top of the small beams. The neutral axis shift may also be determined analytically. The most interesting and important result of these small laboratory experiments is that during the elastic phase and inelastic (cracking) phase the strain distribution is linear through the beam depth. The strain distribution is linear even up to failure.

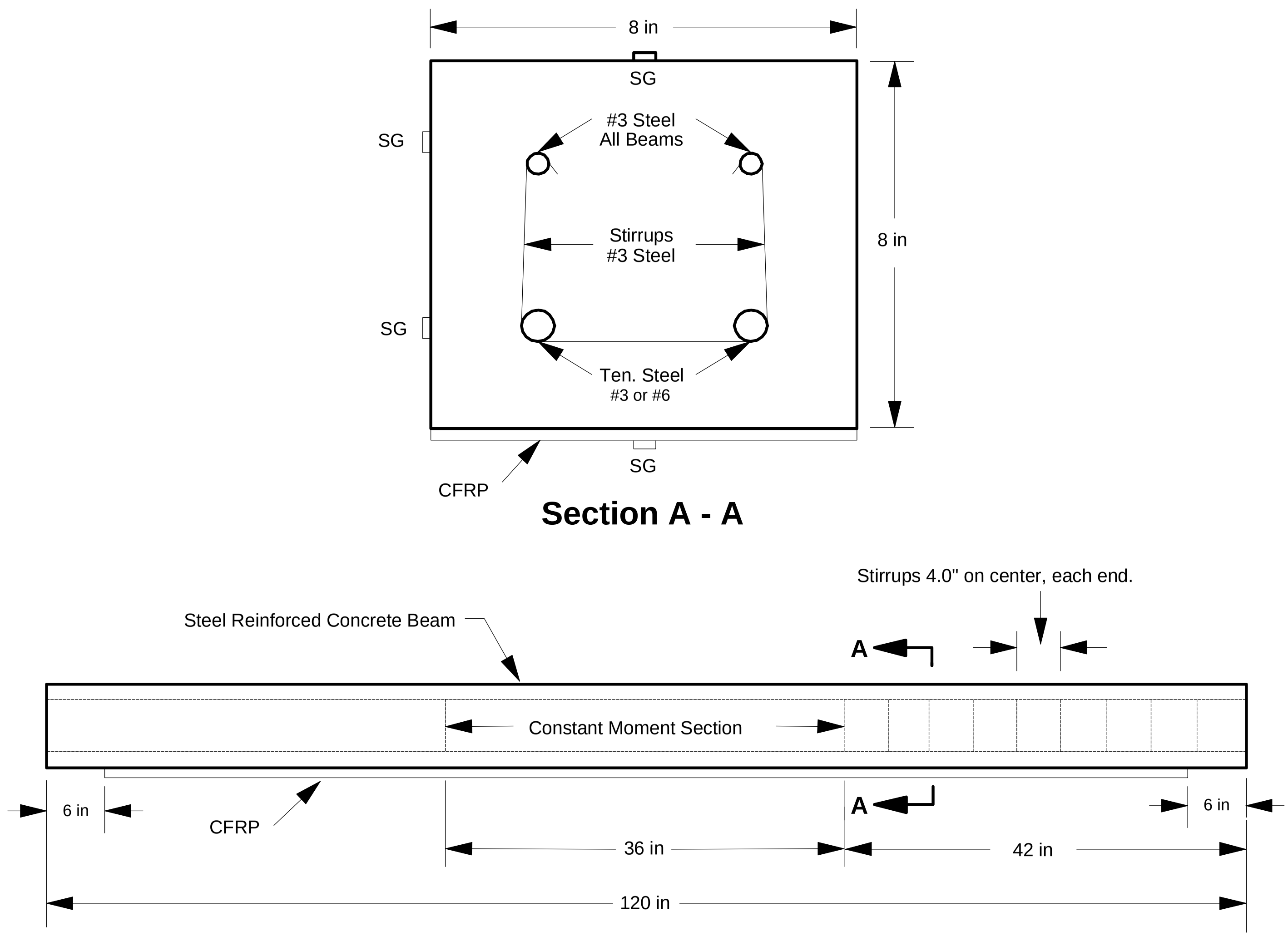

Figure 1. Schematic of 1993 Series Test Beams with Shear Stirrups.

A series of large beam (8 x 8 x 108 in., 0.2 x 0.2 x 2.74 m) tests were initiated in 1993. See Figure 1 for beam configurations and cross sections. The initial beam tests were of unreinforced concrete beams with and without CFRP followed by a series of steel reinforced concrete beams with and without CFRP. A discussion of the plain beams with CFRP applied to the bottom and to bottom and sides is given by Sierakowski et.al.[4] The major results obtained from these tests showed considerable strength enhancement by external placement of CFRP and that the strain through the beam depth is very linear leading to a major assumption that plane sections of the beam remain plane during bending.

Additional large size RC beams with tension rebar sizes of 3, 4, 5,6, 7, and 8 were tested statically in 1994. These tests showed failures of delamination/debonding of 3-ply CFRP from the concrete for steel rebar sizes of five and below and upper compression failure for the beams with steel sizes of six and above. Again, the strain through the beam depth is quite linear. Strength enhancement ratios (peak load with CFRP/peak load without CFRP) of greater than 2.5 at 0.5 percent steel reinforcement ratio and nonlinear down to approximately 1.0 for approximately 4.0 percent steel reinforcement ratio, were obtained experimentally and are shown in Figure 2. The experimental results, the results from a section analysis, and results from a finite element method calculation are given by Ross et.al.[1]

The term “section analysis” as used in this paper and in the previous report[1] is meant to describe a method for calculation of the section properties of the beam cross sectional area. As the concrete cracks in the bending tensile area, the shifting of the neutral axis results in a change in the planar moment of inertia. Also, as the steel becomes inelastic and as the compression zone crushes, both a shift in the neutral axis occurs and is accompanied by a change in the planar moment of inertia. A section analysis is used to track the section properties and in turn, the properties are used to calculate a load displacement curve.

The section analysis coupled with a proposed load displacement curve (given in detail in Reference 1) was used to predict the load displacement for all the beams tested. The results for CFRP/concrete beams with tensile steel ratios below 0.015 were very good. For these beams the CFRP either delaminated or failed in tension. For the higher steel ratios where upper compression failures occurred, the section analysis did not predict peak loads that well. However, for all CFRP/concrete beams up to approximately 50 percent of peak load, the section analysis agreed very well with the experiments. An example of the analysis compared to an experiment is shown in Figure 3. The parameters for this calculation are given in Table 1.

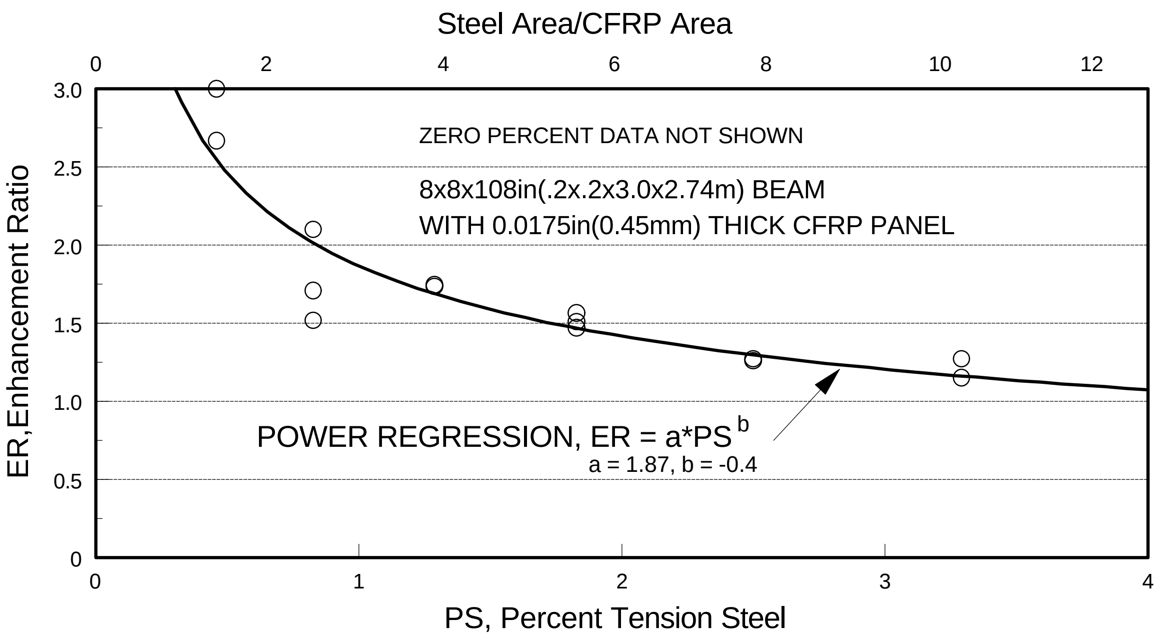

Figure 2. Enhancement Ratios for RC Beams with CFRP Externally Bonded to the Bottom of the Beam.

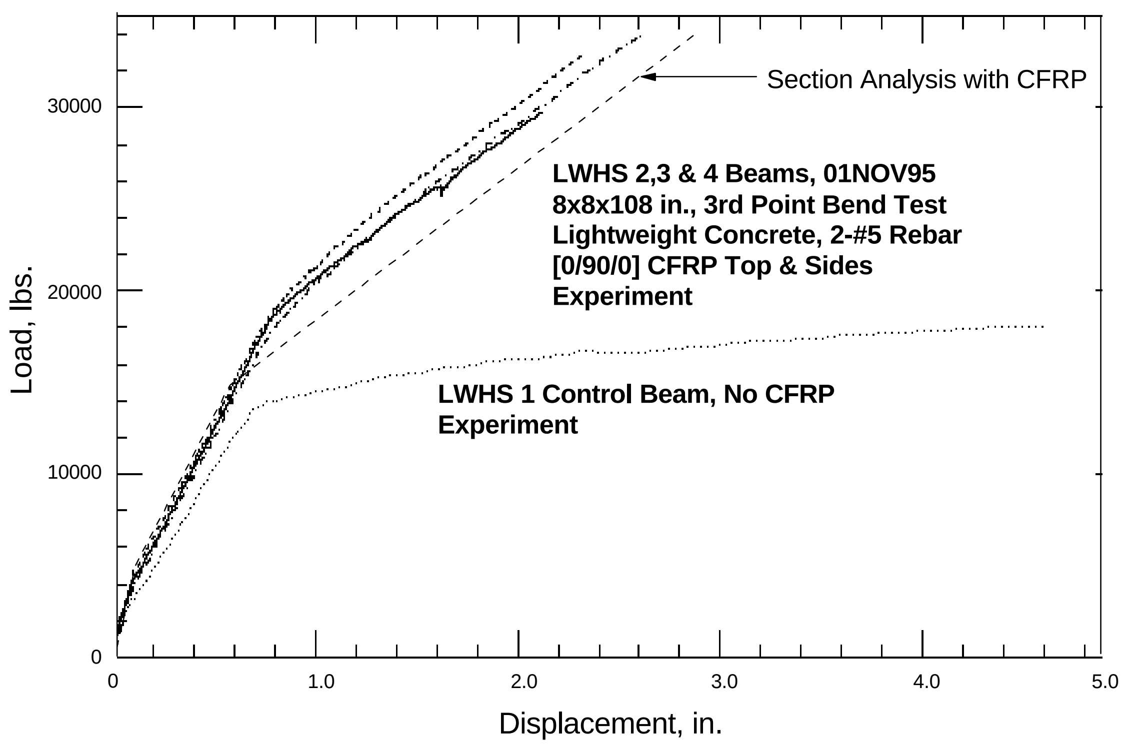

Figure 3. Load-Displacement Curves for LWHS Series.

Table 1. Large Beam Dimensions and Material Properties.

Dimensions:	8 x 8 x 108 in. (0.2 x 0.2 x 2.74 m)
Concrete:	Lightweight high strength (LWHS)
	Strength at time of test:
	Compression = 11,140 psi (76.82 MPa)
	Tension = 510 psi (3.52 MPa)
	Strain at compressive strength = 0.003
	Specific weight = 122 lbs/ft^3
	Density = 1954 kg/m^3
Rebar:	Two No. 5's tension steel, no compression or shear steel
	Tension Strength = 60,000 psi (0.41 GPa)
	Reinforcement ratio = 0.0127
CFRP:	3-Ply AS4/1819, [0^o/90^o/0^o], 60% fiber vol.
	Strength = 0^o tension = 320,000 psi (10.3 GPa)
	90^o tension = 6,000 psi (41.4 MPa)
	Modulus = 0^o tension = 20 x 10^6 psi (138 GPa)
	90^o tension = 1.5 x 10^6 psi (10.3 GPa)
	Thickness = 0.0195 in (0.5 mm)
	CFRP vacuum bonded to bottom and sides of beam using a two-part epoxy adhesive.

During the latter part of 1994 a vacuum bonding technique was developed at the University of Florida to bond CFRP to a series of laboratory specimens to be tested dynamically in the WL/FIVCO drop weight tester. Initially for each application, the bonding technique used two pieces of plastic to form a vacuum bag in which CFRP was cemented to nine small beams. The vacuum process does not have to be a bag. A single sheet of plastic may be used by simply sealing the edges of the plastic sheet along the edges of the CFRP. This new bonding technique allowed the application of approximately 14 psi (0.1 MPa) of vacuum pressure to press the CFRP to the concrete/adhesive surface. In previous adhesive operations, such as the 1993 and 1994 beam fabrication, only approximately 0.5 psi (3.45 kPa) was obtained by using a series of weights on the beams. The vacuum bonding device is shown schematically in Figure 4. The vacuum bond technique was used on the three lightweight-high-strength beams and for these beams the CFRP failed in tension as opposed to the delamination of CFRP of previous tests.

Small laboratory size (3 x 3 x 30 in., 7.62 x 7.62 x 76.2 cm) beams tested dynamically in the drop weight tester, sustained loads in amplitudes up to 10 kips (44.5 kN) and durations less than 1.0 millisecond. Measurements included total load, midspan displacements and strains, and a high-speed framing camera (10,000 frames sec) gave insight into failure mechanisms. Quasi/static bending tests were also conducted on control beams. Dynamic beam bending loads were determined by subtracting inertia loads from the measured drop weight loads. Failure to account for the inertia loads will result in

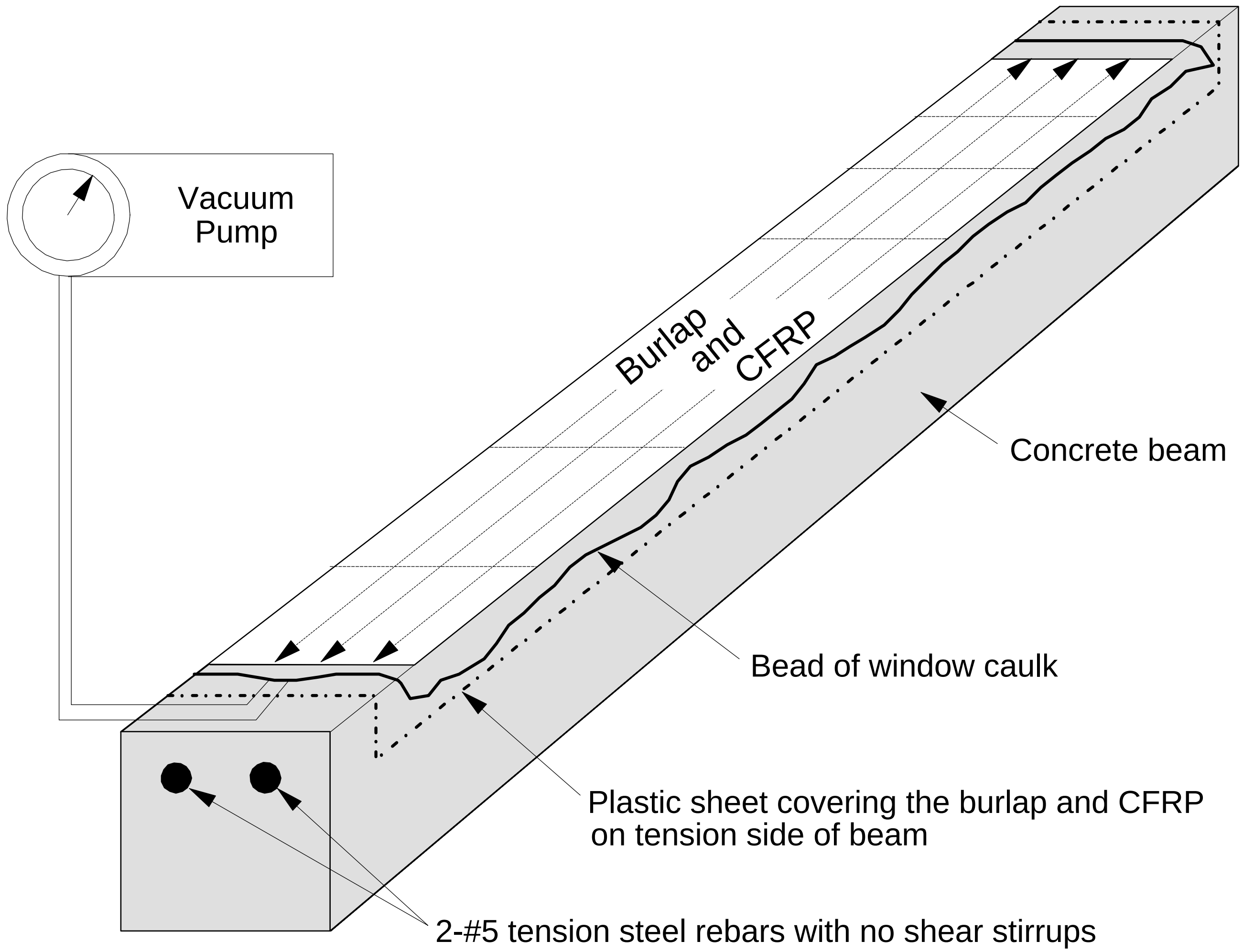

Figure 4. Schematic of Vacuum Bonding Technique Used for the LWHS Series.

incorrect bending loads. Fracture energies were determined by finding the area under the beam bending load versus displacement curve. All dynamic beam fracture energies were less than their static counterpart, but dynamic peak bending loads were two to three times larger than the static values. The description of the vacuum bonding technique and presentation of the experimental dynamic results are given by Jerome[2].

DURABILITY OF CFRP/CONCRETE BEAMS

The objective of this effort was to test and evaluate the effect of environmental conditions on the performance of concrete members strengthened by externally-bonded advanced composite materials. Testing was performed by both non-destructive (NDT) and destructive methods.

Portland cement concrete beams were prepared in the usual manner and moist cured for 28 days. The 2 x 2 x 12 in. (5.08 x 5.08 x 30.48 cm) beams were cast from a mix design referred to as "G-mix." Its composition is given in Table 1.

Table 2. Composition of "G-mix" Portland Cement Concrete.

Component	Wt. in lbs/cubic yard
Type 1 Portland cement	376
3/8 in. max. limestone aggregate	1690
Concrete sand (FM. of 2.1)	1345
Fly ash (Class F)	243
Water	365

The G-Mix water to cement + fly ash ratio was 0.6 and had a 28-day compressive strength of 4250 psi (29.31 MPa). The calculated flexural strength and static modulus of elasticity were 490 psi (3.38 MPa) and 3.7×10^6 psi (25.5 GPa) respectively. One side of each beam was prepared in a like manner by surface scarification. The prepared surfaces were primed with a low viscosity two-part epoxy primer. The bonding of the 2.0-in. wide by 0.0155 in. thick (50.8 x 0.29 mm), 2-ply CFRP strips was performed using a two-part epoxy adhesive having a paste-like consistency. Curing time was seven days at ambient temperature. The properties of the CFRP are given in Table 1.

The test specimens were divided into four groups. Group 1, control samples were externally reinforced concrete beams that were conditioned in a laboratory environment at ambient temperature. Group 2 samples were exposed to QUV according to ASTM G-53, "Operating Light and Water Exposure Apparatus for Exposure of Nonmetallic Materials." This method is intended to simulate deterioration caused by moisture as rain or dew and the ultraviolet energy in sunlight. Test specimens were exposed to test conditions consisting of eight hours of UV at 60^{o}C. and four hours of condensation at 40^{o}C. for a total combined time of 1000 hours. The samples were oriented in such a way that only the externally bonded CFRP reinforcement was exposed to the effects of UV light and condensation. Group 3 samples were exposed to conditions of freezing and thawing according to ASTM C-884, "Thermal Compatibility between Concrete and an Epoxy Resin." The method is intended to evaluate whether or not delamination or the presence of horizontal cracks near the bonded composite-concrete interface has occurred when exposed to five cycles of freezing in air and thawing in air. Each cycle consisted of freezing in air for 24 hours at -18^{o}C. and thawing in air for 24 hours at 25^{o}C. Group 4 samples were exposed to the effects of moisture and temperature according to ASTM D-1151, "Effect of Moisture and Temperature on Adhesive Bonds." This test method is used to determine a material's performance, exposed to a variety of moisture and temperature conditions, based on the ratio of strength retained after exposure to the original strength. The test specimens were exposed to seven days of water immersion at 60^{o}C. followed by seven days of drying and ambient temperature.

Two test methods were used in this study to evaluate the effect of the environmental conditions described previously on the quality of externally bonded CFRP to portland cement concrete (PCC). The first method, ASTM 597, "Pulse Velocity Through Concrete," covers the determination of the pulse velocity of propagation of compressional waves in concrete. This non-destructive test method is used to assess the uniformity and relative quality of concrete and other materials, and to estimate the severity of deterioration or cracking.

In this study, the arrangement of transmitting and receiving transducers are shown in Figure 5. This method is often referred to as the "surface indirect method" for determining cracking and/or delamination at the reinforcing material/concrete interface. As the receiving transducer is moved to different distances x1, x2, x3, and x4, a plot of pulse time versus distance is generated. A straight line function indicates that the interfacial area is free of cracks and delaminations; and on the other hand, a sharp increase in time (reduced pulse velocity) would indicate the presence of a crack or delamination at a given distance from the transmitting transducer.

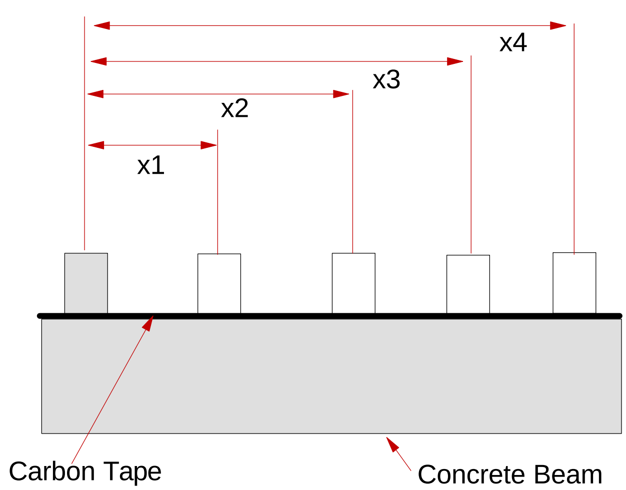

Figure 5. Pulse Velocity Determination on Externally Bonded CFRP - PCC Composites.

The second method, ASTM C-1018, "Flexural Toughness and First-Crack Strength of FRC (Using Beam with Third-Point Loading)," was implemented to evaluate the flexural toughness of the externally bonded CFRP-PCC composites. This method provides for the determination of toughness indices that identify the pattern of material behavior up to a selected deflection criteria. Toughness indices are determined in terms of areas under the load-deflection curve to a specific deflection. Toughness is an indication of the energy absorption capability of a particular test specimen. The test provided for the determination of the first-crack flexural strength using the load corresponding to the point on the load-deflection curve defined as first-crack. The first-crack strength characterizes the behavior of the composite material up to the onset of cracking in the matrix, while the toughness indices characterize the behavior thereafter.

Toughness was also measured by a Japanese standard JCI-SF4, that determined the area under the load-deflection curve up to a deflection corresponding to the span of the test beam divided by 150. In this method, the flexural strength is defined with reference to the maximum load sustained by the test specimen, and measures the area under the load-deflection curve to a greater deflection than the ASTM standard.

Both methods of determining flexural toughness utilized a beam type specimen having a span equal to three times its depth, loaded by third-point loading according to ASTM C-78, and a midspan deflection controlled at a rate of 0.002 to 0.004 in. per minute (0.05 to 0.1 mm/min), see Figure 6.

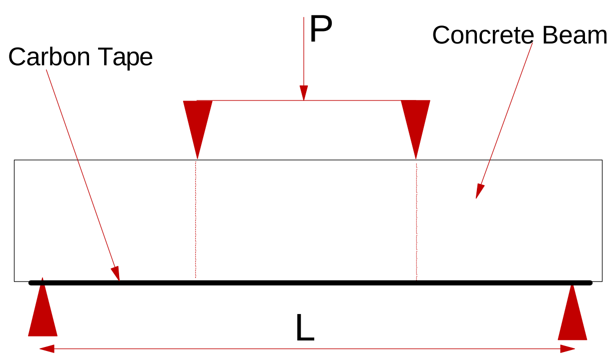

Figure 6. Test Setup for Third-Point Loading of CFRP-PCC Beam Specimens.

CFRP-PCC composite samples appeared to be slightly altered by the environmental exposure of 1000 hours of QUV. The pulse velocity was reduced slightly, thus reducing the dynamic pulse modulus of elasticity of the composite material by less than 15 percent. The exposure to freeze-thaw cycling and hot water immersion did not appear to effect the CFRP-PCC composite materials as determined by NDT.

The results from flexural strength and toughness data indicated no significant reduction in mechanical properties for Group 2, 3 or 4 samples based on ASTM C-1018 criteria for first-crack strength and toughness indices. Additional results are given by Muszynski and Sierakowski.[5]

DYNAMIC SLAB TESTS

An agreement was reached with Israeli officials to conduct full-scale explosive tests (spring 1994) in Israel using 1830 pounds (830 kg) of TNT on structures that had been modified with the composite reinforcing material. The strengthened facilities were capable of surviving an air blast load at relatively short standoff distances. The strengthening procedure employed involved two types of materials: an autoclaved 3-ply carbon fiber composite laminate, and a knitted biaxial fiberglass fabric. WL/FIVCO applied the composite materials in Israel, after the facilities had been constructed, using an epoxy adhesive to affix the composite sheet material to the concrete. This provided a simple, effective, and quick method of retrofitting an existing structure. The free-field and reflected pressures and accelerations on the walls were measured. The results of these tests were successful, considering the fact that the externally reinforced walls suffered high displacements yet did not fail. The pressure and impulse data indicate that both structures would have failed catastrophically without the externally applied composite reinforcing material. Additional results of these tests are given by Muszynski et.al.[6]

BRIDGE REHABILITATION

Many reinforced concrete bridges throughout the United States on county and state highway systems are deteriorated and/or distressed to such a degree that reducing the allowable truck loading on the bridge by load posting is needed to lengthen the remaining life of the bridge. The structural performance of many of these bridges can be improved through the external bonding of FRP laminates. This section describes the rehabilitation of a concrete bridge in rural Alabama through the external bonding of FRP laminates. The bridge rehabilitation project was conducted by Auburn University.

The structure consists of 13 simple spans of 34 ft. (10.34 m) lengths. Each span is comprised of four reinforced concrete T-beams, nearly all of which exhibit significant flexural cracking due to routine truck traffic over a 30-year period. One span from this bridge was retrofitted with the application of FRP laminates. CFRP laminates were applied to the bottoms and glass fiber reinforced plastic (GFRP) laminates to the sides of the stems of the T-beams as shown in Figure 7. The beams were appropriately instrumented to collect the pertinent data from load tests.

Field load tests were performed so that comparisons of the structural behavior of the bridge before and after application of the FRP could be made. The bridge behavior was quantified by measurements of vertical deflections, strains in the primary flexural reinforcement, concrete strains on the surface of the bridge beams, and strains on the

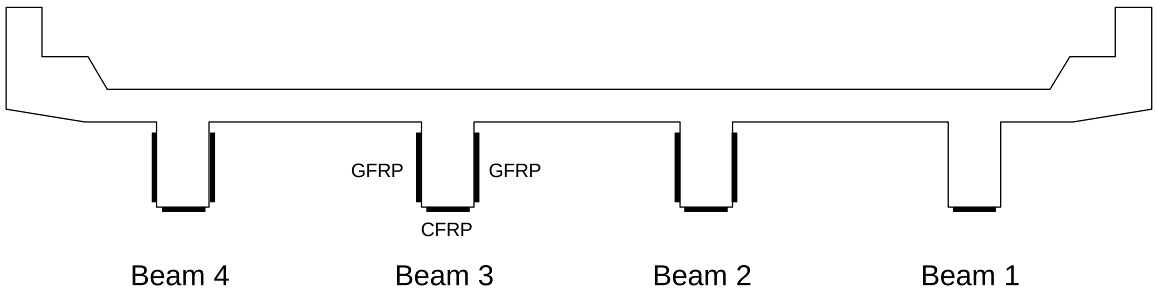

Figure 7. Locations of CFRP and GFRP Laminates for Bridge Rehabilitation.

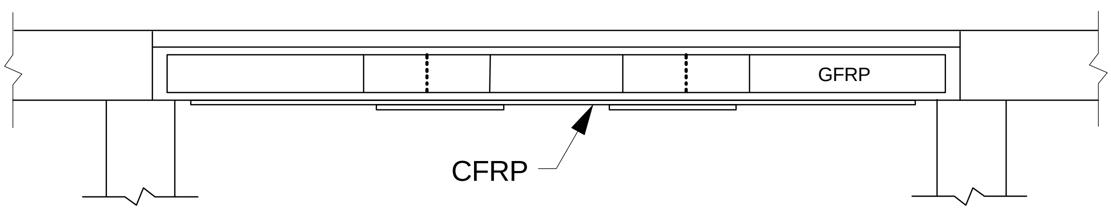

Figure 8. Typical Layout for CFRP and GFRP Laminates for Bridge Rehabilitation.

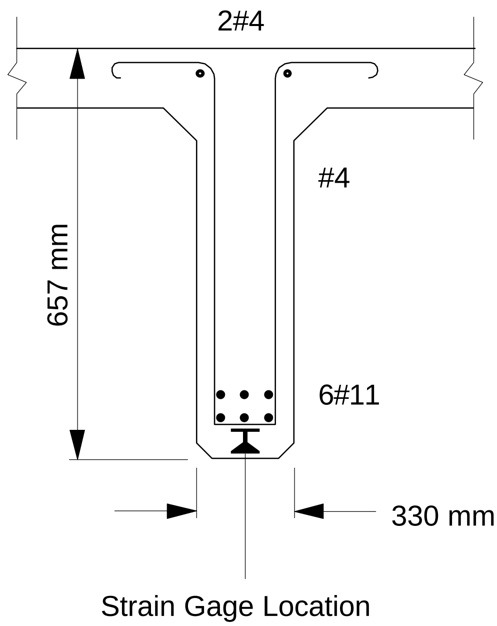

Figure 9. Typical T-Beam Cross Section for Bridge Rehabilitation.

surface of the FRP laminates. Measurements were made for static and dynamic loading from two identical load test trucks. The strain measurements provided data necessary for estimating the level of performance enhancement provided by the FRP.

Unidirectional CFRP laminates were adhered to the bottom surfaces of the T-beams. Three CFRP laminates of 11 ft. (3.4 m) lengths were installed on each beam as shown in Figures 7 and 8. These laminates were 10.5 in. (266 m) wide and 0.04 in. (1 mm) thick, having an elastic modulus of 18 x 10^6 psi (124.1 GPa) and a tensile strength of 174,000 psi (1200 MPa). GFRP laminates of 11 ft. (3.4 m) lengths were adhered to the sides of the beam stems as illustrated in Figure 8. The unidirectional GFRP laminates were 14 in. (356 mm) wide and 0.04 in. (1 mm) thick, having an elastic modulus of 3.0 x 10^6 psi (206.85 GPa) and a tensile strength of 65,250 psi (450 MPa). Splice plates of 3.0 ft. (0.9 M) lengths were used to maintain continuity in both the CFRP and GFRP laminates as shown in Figure 8.

The adhesive used in this project was Dexter Hysol EA9460 structural adhesive, a two component epoxy. This adhesive has a tensile modulus of 0.4 x 10^6 psi (2.76 GPa) and a tensile strength of 4,350 psi (30 MPa). The adhesive was troweled directly onto the laminates which were subsequently pressed to the girder surfaces. Once in place, the laminates were pressurized for approximately seven hours using a vacuum bag technique. The vacuum was maintained between 8 to 10 psi (55,000 - 69,000 pa).

Load tests were conducted both before and after installation of the laminates. Two identical test trucks of known weight provided by the Alabama Department of Transportation were used for the load tests. The test trucks have three axles with a gross vehicle weight of 85.6 kips (381 kN) and an overall length between front an rear axles of 23.3 ft. (7.1 m). Both static and dynamic load tests were conducted using side-by-side truck loading.

To collect the appropriate data, LVDTs were installed at the midspan of each girder, and strain gages were installed on the middle reinforcing bar of the bottom row of reinforcement in each beam as shown in Figure 9. For the post-retrofit load tests, additional strain gages were placed on the bottom and side FRP laminates at the midspan of each beam. Strain gages were also installed on one of the bottom splice plates of one of the interior girders.

The percent changes in axial strain in the reinforcing steel and the percent change in midspan deflections, for each girder, in the pre- and post-retrofit load tests are summarized in Tables 3 and 4 respectively. The load positions indicated for the static tests represent different transverse locations of side-by-side trucks.

Table 3. Percent Change in Reinforcing Steel Strain for Bridge Rehabilitation.

Load Type	**Load Position**	**% Change in Deflection**			
		Beam 1	**Beam 2**	**Beam 3**	**Beam 4**
Static	1	-7	-7	-9	-9
	2	-4	-7	-8	-8
	3	-4	-8	-11	-10
	4	-6	-9	-11	-10
Dynamic	W-E	-4	-8	-14	-14

Table 4. Percent Change in Midspan Beam Deflection for Bridge Rehabilitation

Load Type	**Load Position**	**% Change in Deflection**			
		Beam 1	**Beam 2**	**Beam 3**	**Beam 4**
Static	1	-8	-8	-10	-12
	2	-5	-8	-9	-12
	3	-2	-8	-10	-12
	4	-4	-9	-11	-12
Dynamic	W-E	-8	-12	-16	-11

CONCLUSIONS

External bonding of very thin high-modulus, high-strength fiber reinforced plastic panels to concrete structures has been shown to give increased stiffness and larger load carrying capacity. Experimental and analytical results have verified that these advanced composite materials are very useful and practical in increased hardening and rehabilitation of existing concrete structures. Both nondestructive and destructive test methods show that laboratory CFRP/concrete beams show small detrimental effects as a result of environmental exposure to freeze-thaw cycling and ultraviolet light. The energy absorbing capacity of CFRP/concrete beams was increased by a factor of 50 over that of control beams, when tested statically.

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